THE SCIENTIFIC MONTHLY

JULY, 1916

THE ORIGIN AND EVOLUTION OF LIFE UPON THE EARTH[1]

BY HENRY FAIRFIELD OSBORN

COLUMBIA UNIVERSITY, AMERICAN MUSEUM OF NATURAL HISTORY

LECTURE I. PART I

INTRODUCTION

WE may introduce this great subject by putting to ourselves four leading questions: first, is life something new; second, is life evolution the same as stellar evolution; third, is there evidence that similar physico-chemical laws prevail in life and in lifeless evolution; fourth, are life forms the result of law or of chance?

First: does the origin of life[2] represent the beginning of something new in the cosmos, or does it represent the continuation and evolution of forms of matter and energy already found in the earth, in the sun, and in the other stars? This is the first question which occurs to us, and it is one which has not yet been answered. The more traditional opinion is that something new entered this and possibly other planets with the appearance of life; this is also involved in all the older and newer hypotheses which group around the idea of vitalism or the existence of specific, distinctive and adaptive energies in living matter. The more modern scientific opinion is that life arose from a recombination of forces preexisting in the cosmos. To hold to this answer, that life does not represent the entrance either of a new form of matter or of a new series of laws but is simply another step in the general evolutionary process, is certainly consistent with the development of me-

1 Fourth course of lectures on the William Ellery Hale Foundation, National Academy of Sciences, delivered at the meeting of the academy at Washington, on April 17 and 19, 1916. The author is greatly indebted for many notes and suggestions in physics and chemistry to his colleagues in the National Academy and Columbia University, especially to M. I. Pupin, F. W. Clarke, G. F. Becker and W. J. Gies.

2 In order to consider this problem from a fresh, unbiased, and original point of view the author has purposely refrained from reading the recent treatises of Shafer, Moore and others on the origin of life. In the chemical section the author is, however, indebted to the very suggestive work of Henderson entitled "The Fitness of the Environment."

chanics, physics and chemistry since the time of Newton and of evolutionary thought since Lamarck and Darwin.

Second: the second question relates to the exact significance of the term *evolution* when applied to lifeless and to living matter. Is the development of life evolutionary in the same sense or is it essentially different from that of the inorganic world? Let us critically examine this question by comparing the evolution of life with what is known of the evolution of matter, of the evolution of the stars, of the formation of the earth; in brief, of the comparative anatomy and physiology of the universe as developed in the preceding lectures of this course by Rutherford,[3] Campbell,[4] and Chamberlin;[5] of the possible evolution of the chemical elements themselves from simpler forms, in passing from primitive nebulæ through the hotter stars to the planets, as first pointed out by Clarke[6] in 1873, and by Lockyer in 1874.

Do we find a correspondence between the orderly development of the stars and the orderly development of life? Do we observe in life a continuation of processes which in general have given us a picture of the universe slowly cooling off and running down; or, after hundreds of millions of years of more or less monotonous repetition of purely physico-chemical and mechanical reaction, do we find that electrons, atoms, and molecules break forth into new forms and manifestations of energy which appear to be "creative," conveying to our eyes at least the impression of incessant genesis of new combinations of matter, of energy, of form, of function, of character?

To our senses it seems as if the latter view were the correct one, as if something new had been breathed into the aging dust, as if the first appearance of life on this planet marked an actual reversal of the previous order of things. Certainly the cosmic processes cease to run down and begin to build up, abandoning old forms and constructing new ones. Through these activities within matter in the living state the dying earth, itself a mere cinder from the sun, develops new chemical compounds; the chemical elements of the ocean are enriched from new sources of supply, as additional amounts of chemical compounds, produced by organisms from the soil or by elements in the earth that were not previously dissolved, are liberated by life processes and ultimately carried out to sea; the very composition of the rocks is changed; a new life crust begins to cover the earth and to spread over the bottom of the sea. Thus our old inorganic planet is reorganized, and we see in living matter a reversal of the melancholy conclusion reached by Campbell[7] that

3 Rutherford, Sir Ernest, 1914.

4 Campbell, William Wallace, 1914.

5 Chamberlin Thomas Chrowder, 1916.

6 Clarke, F. W., 1873, p. 323.

7 Campbell, William Wallace, 1915, p. 209.

Everything in nature is growing older and changing in condition; slowly or rapidly, depending upon circumstances; the meteorological elements and gravitation are tearing down the high places of the earth; the eroded materials are transported to the bottoms of valleys, lakes and seas; and these results beget further consequences.

Thus, in answer to our second question, it certainly appears that *living matter does not follow the old evolutionary order* but represents a new assemblage of energies and new types of action, reaction, and interaction—to use the terms of Newton—between those chemical elements which are as old as the cosmos itself, unless they prove to represent, as Clarke, Lockyer, and Rutherford have suggested, an evolution from still simpler elements.

Third, is there a continuation of the same physico-chemical laws? Yes, so far as we observe, the process is still *evolutionary rather than creative,* because all these new characters and forms invariably arise out of new combinations of preexisting matter and appear to broadly conform to the laws of thermodynamics, and especially to Newton's third law. According to the interpretation by Pupin of this third law of Newton, *action* and *reaction* refer to what is going on between material parts in actual contact, whereas *interaction* refers to what is going on between two material parts which are connected with each other by other parts. Action and reaction are simultaneous, whereas interaction refers to an action and reaction which are not simultaneous. For example, when one pulls at a line the horse feels it a little later than the moment at which the line is pulled; there is interaction between the hand and the horse's mouth, the line being the interconnecting part.

In this lecture I shall attempt to show that since in their *simple* forms living processes are known to be physico-chemical and are more or less clearly interpretable in terms of action, reaction and interaction, we are compelled to believe that *complex* forms will also prove to be interpretable in the same terms.

If we affirm that the entire trend of our observation is in the direction of the physico-chemical rather than of the vitalistic hypotheses this is very far from affirming that the explanation of life is purely materialistic or that any present physico-chemical explanation is either final or satisfying to our reason. Chemists and biological chemists have very much more to discover. May there not be in the assemblage of cosmic chemical elements necessary to life, which we shall distinguish as the *"life elements,"* some *known* element which thus far has not betrayed itself in chemical analysis? This is not impossible, because a known element like radium, for example, might well be wrapped up in living matter but as yet undetected, owing to its suffusion or presence in excessively small quantities or to its possession of qualities that have escaped notice. Or, again, an *unknown* chemical element, to which the

hypothetical term *bion* might be given, may lie awaiting discovery within this complex of known elements. Or an unknown source of energy may be active here. Or, as is far more probable from our present state of knowledge, unknown principles of action, reaction and interaction may await discovery: such principles are indeed adumbrated in the as yet partially explored activities of the catalytic agents in living chemical compounds.

In answer to our first main question, to which we now return, we may express as our own opinion, based upon the logical application of uniformitarian evolutionary principles, that when life appeared some energies preexisting in the cosmos were brought into relation with the elements or forces already existing. In other words, since every advance thus far in the quest as to the nature of life has been in the direction of a physico-chemical rather than a vitalistic explanation, from the time when Lavoisier (1743–1794) put the life of plants on a solar-chemical basis, logically following the same direction, we believe that the last step into the unknown—one which possibly may never be taken by man—will also be physico-chemical in all its measurable and observable properties, and that the origin of life, as well as its development, will ultimately prove to be a true evolution within the preexisting cosmos.

None the less, such evolution, we repeat with emphasis, is not like that of the chemical elements or of the stars; the evolutionary process now takes an entirely new and different direction. Although it arises through combinations of preexisting energies it is essentially constructive and creative; it is continually giving birth to an infinite variety of new forms and functions which never appeared in the universe before. While this creative power is something new derived from the old, it presents the first of the numerous contrasts between the living and the lifeless world.

We are now prepared for the fourth of our leading questions. It having been determined that the evolution of non-living matter follows certain physical laws and that the living world conforms to many if not to all of these laws the final question which arises is: does the living world also conform to law in its most important aspect, namely, that of fitness or adaptation, or does law emerge from chance?

Let us first make clear the distinction between law and chance. On this a physicist (M. I. Pupin) observes:

> In physics, when distinguishing between law and chance, we speak of coordinated phenomena like planetary motions, and of *non-coordinated* phenomena like the motion of individual molecules in a large number of molecules. In regard to such motion, chance or probability or so-called statistical modes of procedure guide the reasoning. Again, *radiation* is a statistical or non-coordinated mode of procedure, and since it is closely related to the growth of plants (the simplest forms of life) why is not life in its constituent elements a statistical or chance procedure? May not life-forms and life itself be differentiated just like the motion of radiating atoms and observable forms of radiation?

Although the motions giving rise to radiation are haphazard, the resulting forms of radiation which we observe are definite and beautifully arranged as if they proceeded from perfectly coordinated and not from perfectly haphazard motions.

It is obvious that the answer to these questions put by a physicist may be reached in biology through observation.

Campbell has described the orderly development of the stars and Chamberlin the orderly development of the earth: is there also an orderly development of life? Are life forms, like celestial forms, the result of law or are they the result of chance? This is perhaps the very oldest biologic question that has entered the human mind, and it is one on which the widest difference of opinion exists even to-day.

Chance has been the opinion held by a great line of philosophers from Democritus and Empedocles to Darwin, and including Poulton, de Vries, Bateson, and many others of our own day: chance is the very essence of the Darwinian selection hypothesis of evolution. William James[8] and many other eminent philosophers have adopted the "chance" view as if it had been actually demonstrated, instead of being, as it is, one of the string of hypotheses upon which Darwin hung his theory of the origin of adaptations and of species. To quote the opinion of a recent writer:

And why not? Nature has always preferred to work by the hit or miss methods of chance. In biological evolution millions of variations have been produced that one useful one might occur.[9]

I have long maintained that this opinion is a biological dogma[10] which has gained credence through constant reiteration, for I do not know that it has ever been demonstrated through the actual observation of any evolutionary series.

Law has been the opinion of another school of natural philosophers, headed by Aristotle, the opponent of Democritus and Empedocles. This opinion has fewer philosophical and scientific adherents; yet Eucken,[11] following Schopenhauer, has recently expressed it as follows:

From the very beginning the predominant philosophical tendency has been against the idea that all the forms we see around us have come into existence solely through an accumulation of accidental individual variations, by the mere blind concurrence of these variations and their actual survival, without the operation of any inner law. Natural science, too, has more and more demonstrated its inadequacy.

Unlike our first question as to whether the principle of life introduced something new in the cosmos, a question which is still in the stage of pure speculation, this fourth question of law versus chance in the

[8] James, William, 1902, pp. 437–439.

[9] Davies, G. R., 1916, p. 583.

[10] Biology like theology has its dogmas. Leaders have their disciples and blind followers. All great truths, like Darwin's law of selection, acquire a momentum which sustains half-truths and pure dogmas.

[11] Eucken, Rudolf, 1912, p. 257.

evolution of life is no longer a matter of opinion, but of direct observation. So far as law is concerned life forms are like those of the stars: their origin and development as revealed through paleontology go to prove that Aristotle was essentially right when he said that "Nature produces those things which, being continually moved by a certain principle contained in themselves, arrive at a certain end."[12] What this internal moving principle is remains to be discovered. We may first exclude the possibility that it acts either through supernatural or teleologic interposition; and although its visible results are in a high degree purposeful we may exclude as unscientific the vitalistic theory of an *enteleche* or any other form of distinct internal perfecting agency. The fact that the principle underlying many complex forms of adaptation is still unknown, unconceived, and perhaps inconceivable, does not inhibit our opinion that adaptation will prove to be a continuation of the previous cosmic order. Since certain forms of adaptation which were formerly mysterious can now be explained without the assumption of an *enteleche,* it follows that all forms of adaptation may some day be explained in the same way.

But if we reject the vitalistic hypotheses we are driven back to the necessity of further physico-chemical analysis and research.

We shall discover that the first striking phenomenon in life is the *extraordinary complexity of the actions, reactions and interactions of forces which gradually evolves.* This complex of four interrelated sets of physico-chemical energies which I have previously adumbrated[13] as the most fundamental biologic law may now be restated as follows:

Actions, Reactions and Interactions of

1. The Cosmic Environment (physico-chemical energies).
2. The Individual Development (biochemical energies of the developing individual).
3. The Chromatin (biochemical energies of the heredity substance).
4. The Life Environment (biochemical energies of other individuals).

Selection

Competition with other individuals (factors of Natural Selection and Elimination, leading to survival or extinction).

This law I shall put forth in different aspects as the central thought of these lectures, stating at the outset that it involves an unknown prin-

[12] Osborn, H. F., 1894, p. 56.

[13] In several previous statements and definitions of this law I have termed it the law of the four inseparable factors of evolution, including environment (organic and inorganic), individual development, heredity (the chromatin) and selection. I now perceive that selection should not be included with the other factors because it is no sense coordinate. The causes of the origin and evolution of life must lie entirely within the physico-chemical and biochemical cycle. Osborn, H. F.

ciple, namely, the nature of the action, reaction, and interaction of the cosmic and life environment and individual developmental energies with the energies of the heredity substance. The nature of this unknown principle,[14] which is at present almost entirely beyond the realm of observation and experiment, will, however, be made clearer through the development of our main subject, the *origin and evolution of life upon the earth so far as it has been observed up to the present time or so far as it can be legitimately inferred from actual observation.*

The Earth as a Developing Environment

In general, our narrative will follow the "uniformitarian" method of interpretation first presented in 1788 by Hutton,[15] who may be termed the Newton of geology, and elaborated in 1830 by Lyell,[16] the master of Charles Darwin. In the spirit of the preparatory work of the great pioneers in geology, such as Hutton, Scrope and Lyell, and of the history of the evolution of the working mechanism of organic evolution, as developed by Darwin and Wallace,[17] our inferences as to past processes are founded upon the observation of present processes. The uniformitarian doctrine is this: present continuity implies the improbability of past catastrophism and violence of change, either in the inorganic or in the organic world.

We shall consider in order, first, the evolution of the inorganic environment necessary to life; second, the advent of life, what is known of its nature and in regard to the time and the form in which it probably originated; and third, the evolution of life, its orderly development, the differentiation and adaptation of the various life forms; while throughout we shall trace the operation of our fundamental biologic law, which involves the action, reaction and interaction of environment and individual development with the forces of heredity.

PRIMORDIAL ENVIRONMENT—THE LIFELESS EARTH

Let us first look at the cosmic environment, the inorganic world before the entrance of life. Since 1825, when Cuvier[18] published his famous "Discours sur les Revolutions de la Surface du Globe," the past history of the earth, of its waters, of the atmosphere, and of the sun—the four great complexes of inorganic environment—has been written with some approach to precision. Astronomy, physics, chemistry, geology and paleontology have each followed along their respective lines of observation, resulting in some concordance and much discordance of opinion and theory. In general we shall find that opinion founded

14 See Osborn, H. F., 1909, 1912, 1, 1912, 2.

15 Hutton, James, 1795.

16 Lyell, Charles, 1830.

17 Judd, John W., 1910.

18 Cuvier, Baron Georges L. C. F. D., 1825.

upon life data has not agreed with opinion founded upon physical or chemical data. Discord has arisen especially in connection with the age of the earth and the stability of the earth's surface. In our review of these matters we may glance at opinions of all kinds, whatever their source; but our main narrative of the chemical origin and history of life on the earth will be followed by observations on living matter as it is revealed in paleontology and as it exists to-day, and not on hypotheses and speculations upon preexisting states.

The formation of the earth's surface is a prelude to our considering the first stage of the environment of life. According to the planetesimal theory, as set forth by Chamberlin[19] in the preceding lectures, the earth, instead of consisting of a primitive molten globe as postulated by the old nebular hypothesis originated in a nebulous knot of solid matter as a nucleus of growth which was fed by the infall or accretion of scattered nebulous matter (planetesimals) coming within the sphere of control of this knot. The temperature of these accretions to the early earth could scarcely have been high, and the mode of addition of these planetesimals one by one explains the very heterogeneous matter and differentiated specific gravity of the continents and oceanic basins. The present form of the earth's surface is the result of the combined action of the lithosphere, hydrosphere, and atmosphere. Liquefaction of the rocks occurred locally and occasionally as the result of heat generated by increased pressure and by radioactivity; but the planetesimal hypothesis assumes that the elastic rigid condition of the earth, as at present, prevailed—at least in its outer half—throughout the history of its growth from the small original nebular knot to its present proportions and caused the permanence of its continents and of its oceanic basins. We are thus brought to conditions that are fundamental to the evolution of life on the earth. According to the opinion of Chamberlin cited by Pirsson and Schuchert,[20] life on the earth may have been possible when it attained the present size of Mars.

According to Becker,[21] who follows the traditional theory of a primitive molten globe, the earth first presented a nearly smooth, equipotential surface, determined not by its mineral composition, but by its density. As the surface cooled down a temperature was reached at which the waters of the gaseous envelope united with the superficial rocks and led to an aqueo-igneous state. After further cooling the second and final consolidation followed, dating the origin of the granites and granitary rocks. The areas which cooled most rapidly and best conducted heat formed shallow oceanic basins, whereas the areas of poor conductivity which cooled more slowly stood out as low continents. The internal heat of the cooling globe still continues to do its work, and the

19 Chamberlin, Thomas Chrowder, 1916.

20 Pirsson, Louis V., and Schuchert, Charles, 1915, p. 535.

21 Becker, George F., letter of October 15, 1915.

cyclic history of its surface is completed by the erosion of rocks, by the accumulation of sediments, and by the following subsidence of the areas loaded down by these sediments. It appears that the internal heat engine is far more active in the slowly cooling continental areas than in the rapidly cooling areas underlying the oceans, as manifested in the continuous outflows of igneous rocks, which, especially in the early history of the earth—at or before the time when life appeared—covered the greater part of the earth's surface. The ocean beds, being less subject to the work of the internal heat engine, have always been relatively plane; except near the shores, no erosion has taken place.

The Age of the Earth

The age of the earth as a solid body affords our first instance of the very wide discordance between physical and biological opinion. Among the chief physical computations are those of Kelvin, Sir George Darwin, and King and Barus.[22] In 1879 Sir George Darwin allowed 56 million years as a probable lapse of time since the earth parted company with the moon, and this birthtime of the moon was naturally long prior to that stage when the earth, as a cool crusted body, became the environment of living matter. Far more elastic than this estimate was that of Lord Kelvin, who, in 1862, placed the age of the earth as a cooling body between 20 and 400 million years, with a probability of 98 million years. Later, in 1897, accepting the conclusions of King and Barus calculated from data for the period of tidal stability, Kelvin placed the age limit between 20 and 40 million years, a conclusion very unwelcome to evolutionists.

As early as 1859 Charles Darwin led the biologists in demanding an enormous period of time for the processes of evolution, being the first to point out that the high degree of evolution and specialization seen in the invertebrate fossils at the very base of the Paleozoic was in itself a proof that pre-Paleozoic evolution occupied a period as long as or even longer than the post-Paleozoic. In 1869 Huxley renewed this demand for an enormous stretch of pre-Cambrian time; and as recently as 1896 Poulton[23] found that 400 million years, the greater limit of Kelvin's original estimate, was none too much. Later physical computations greatly exceeded this biological demand, for in 1908 Rutherford[24] estimated the time required for the accumulation of the radium content of a uranium mineral found in the Glastonbury granitic gneiss of the Early Cambrian as no less than 500 million years.

This estimate of the age of the Early Cambrian is eighteen times as great as that attained by Walcott[25] in 1893 from his purely geologic

[22] Becker, George F., 1910, p. 5.
[23] Poulton, Edward B., 1896, p. 808.
[24] Rutherford, Sir Ernest, 1906, p. 189.
[25] Walcott, Charles D., 1893, p. 675.

computation of the time rates of deposition and maximum thickness of strata from the base of the Cambrian upwards; but recent advances in our knowledge of the radioactive elements preclude the possibility of any trustworthy determination of the age of the elements through the methods suggested by Joly and Rutherford.

We thus return to the estimates based upon the time required for the deposition of stratified rocks as by far the most reliable, especially for our quest of the beginning of the life period, because erosion and sedimentation imply conditions of the earth, of the water, and of the atmosphere more or less comparable to those under which life is known to exist. These geologic estimates, which begin with that of John Phillips in 1860, may be tabulated as follows:

TIME REQUIRED FOR THE PROCESSES OF PAST DEPOSITION AND OF SEDIMENTATION AT RATES SIMILAR TO THOSE OBSERVED AT THE PRESENT DAY[26]

1860.	John Phillips	38– 96 million years.
1890.	De Lapparent	67– 90 million years.
1893.	Walcott (27,640,000 years since the base of the Cambrian Paleozoic; 17,5000,000 years or upwards for the pre-Paleozoic.)	55– 70 million years.
1899.	Geikie (Minimum 100 million years; maximum—slowest known rates of deposition—400 million years.)	100–400 million years.
1909.	Sollas (The larger estimate of 80 million years on the theory that pre-Paleozoic sediments took as much time as those from the base of the Cambrian upwards, allowing for gaps in the stratigraphic column.)	34– 80 million years.

These estimates give a maximum of 64 miles as the total amount of sedimentation, which is equivalent to a layer 2,300 feet thick over the entire face of the earth.[27] From these purely geologic data the time ratio of the entire life period is now calculated in terms of millions of years, assuming the approximate reliability of the geologic time scale. The actual amount of rock weathered and deposited was probably far greater than that which has been preserved.

In general these estimates are broadly concordant with those reached by an entirely different method, namely, the amount of sodium chloride (common salt) contained in the ocean, to understand which we must take another glance at the primordial earth.

The lifeless primordial earth can best be imagined by looking at the lifeless surface of the moon, featured by volcanic action with little erosion or sedimentation. The surface of the earth, then, was chiefly

[26] Becker, George F., 1910, pp. 2, 3, 5.
[27] Clarke, F. W., 1916, p. 30.

spread with the granitic batholiths and the more superficial volcanic outpourings. There were volcanic ashes; there were gravels, sands, and micas derived from the granites; there were clays from the dissolution of granitic feldspars; there were loam mixtures of clay and sand; there was gypsum from mineral springs. Bare rocks and soils were inhospitable ingredients for any but the most rudimentary forms of life, such as were adapted to feed directly upon the chemical elements and their simplest compounds or to transform their energy without the friendly aid of sunshine. The only forms of life to-day which can exist in such an inhospitable environment as that of the lifeless earth are certain of the simplest bacteria.

It is interesting to note that in the period when the sun's heat was partly shut off by vapors the *early volcanic condition of the earth's surface* may have supplied life with fundamentally important chemical elements as well as with the heat-energy of the waters or of the soil. Volcanic emanations contain[28] free hydrogen, both oxides of carbon, and frequently hydrocarbons such as methane (CH_4) and ammonium chloride: the last compound is often very abundant. Volcanic waters sometimes contain ammonium (NH_4) salts, from which life may have derived its first nitrogen supply. In the Devil's Inkpot, Yellowstone Park, ammonium sulphate forms 83 per cent. of the dissolved saline matter: it is also the principal constituent of the mother liquor of the boric fumaroles of Tuscany, after the boric acid has crystallized out. A hot spring on the margin of Clear Lake, California, contains 107.76 grains per gallon of ammonium bicarbonate.

There were absent in the primordial earth the greater part of the fine sediments and detrital material which now cover three-fourths of the earth's surface, and from which a large part of the sodium content has been leached. The original surface of the earth was thus composed of igneous rocks to the exclusion of all others,[29] the essential constituents of these rocks being the lime-soda feldspars from which the sodium of the ocean has since been leached. Waters issuing from such rocks are, as a rule, *relatively* richer in silica than waters issuing from modern sedimentary areas. They thus furnished a favorable environment for the development of such low organisms (or their ancestors) as the existing diatoms, radiolarians, and sponges. These have skeletons composed of hydrated silica, mineralogically of opal.

The decomposition and therefore the erosion of the massive rocks was slower then than at present for none of the life agencies of bacteria, of algæ, of lichens, and of the higher plants, which are now at work on granites and volcanic rocks in all the humid portions of the earth, had yet appeared. On the other hand, much larger areas of these rocks were exposed than at present. In brief, to imagine the primal

[28] Clarke, F. W., 1916, Chap. VIII., also pp. 197, 199, 243, 244.

[29] Becker, George F., 1910, p. 12.

earth we must deduct all those portions of mineral deposits which as they exist to-day are mainly of organic origin, such as the organic carbonates and phosphates of lime,[30] the carbonaceous shales as well as the carbonaceous limestones, the graphites derived from carbon, the silicates derived from diatoms, the iron deposits made by bacteria, the humus of the soil containing organic acids, the soil derived from rocks which are broken up by bacteria, and even the ooze from the ocean floor, both calcareous and siliceous, formed from the shells of foraminifera and the skeletons of diatoms. Thus, before the appearance of bacteria, of algæ, of foraminifera, and of the lower plants and lowly invertebrates, the surface of the earth was totally different from what it is at present; and thus the present chemical composition of terrestrial matter, of the sea, and of the air, as indicated by Table I, is by no means the same as its primordial composition sixty million years ago.

TABLE I

AVERAGE DISTRIBUTION OF THE ELEMENTS IN EARTH, AIR AND WATER AT THE PRESENT TIME[31]

	Lithosphere, 93 Per Cent.	Hydrosphere, 7 Per Cent.	Atmosphere	Average, Including Atmosphere
Oxygen	47.17	85.79	20.8 (variable to some extent)	49.85
Silicon	28.00	......	....	26.03
Aluminum	7.84	......	....	7.28
Iron	4.44	......	....	4.12
Calcium	3.42	.05	....	3.18
Magnesium	2.27	.14	....	2.11
Sodium	2.43	1.14	....	2.33
Potassium	2.49	.04		2.33
Hydrogen	.23	10.67	variable	.97
Titanium	.44	......	....	.41
Carbon	.19	.002	variable	.19
Chlorine	.06	2.07	....	.40
Bromine	....	.008	....	
Phosphorus	.11	......	....	.10
Sulphur	.11	.09	....	.10
Barium	.09	......	....	.09
Manganese	.08	......	....	.08
Strontium	.03	......	....	.03
Nitrogen	....	......	78.0 (variable to some extent)	.03
Fluorine	.10	......	....	.10
All other elements	.50	......	....	.47

30 It seems improbable that organisms originally began to use carbon or phosphorus in *elementary* form: carbonates and phosphates were probably available at the very beginning and resulted from oxidations of decompositions.—W. J. Gies.

Phosphate of lime, apatite, is an almost ubiquitous component of igneous rocks, but in very small amount. In more than a thousand analyses of such rocks, the average percentage of P_2O_5 is 0.25 per cent.—F. W. Clarke.

31 Clarke, F. W., 1916, p. 34.

In Table I all the "life elements" which enter more or less freely into organic compounds are indicated by italics, showing that life has taken up and made use of practically all the chemical elements of frequent occurrence with the exception of aluminum, barium and strontium, which are extremely rare in life compounds, and of titanium, which thus far has not been found in any. But even these elements appear in artificial organic compounds, showing combining capacity without biological "inclination" thereto. In the life compounds, as in the lithosphere and hydrosphere, it is noteworthy that the elements of least atomic weight predominate over the heavier elements.

PRIMORDIAL ENVIRONMENT—THE LIFELESS WATER

According to the theory of Laplace the waters originated in the primordial atmosphere; according to the planetesimal theory of Chamberlin[32] and Moulton[33] the greater volume has been gradually added from the interior of the earth through the vaporous discharges of hot springs. As Suess observes,

> The body of the earth has given forth its ocean.

From the beginning of Archeozoic time, namely, for eighty million years, we have little biologic or geologic evidence as to the stability of the earth. From the beginning of the Paleozoic, namely, for a period of thirty million years, the earth has been in a condition of such stability that the oceanic tides and tidal currents were similar to those of the present day; for the early strata are full of such evidences as ripple marks, beach footprints, and other proofs of regularly recurrent tides.[35]

As in the case of the earth, the chemistry of the seas is a matter of inference, *i. e.*, of subtraction. The relatively simple chemical content of the primordial seas must be inferred by deducting the mineral and organic products which have been sweeping into the ocean from the earth during the last eighty to ninety million years; and also by deducting those that have been precipitated as a result of chemical reactions, calcium chloride reacting with sodium phosphate, for example, to yield precipitated calcium phosphate and dissolved sodium chloride.[36] The present waters of the ocean are rich in salts which have been derived by solution from the rocks of the continents.

Thus we reach our first conclusion, namely: it is probable that life originated on the continents, either in the moist crevices of rocks or soils, in the fresh waters of continental pools, or in the slightly saline waters of the bordering primordial seas.

As long ago as 1715 Edmund Halley suggested that the amount of

[32] Chamberlin, Thomas Chrowder, 1916 .

[33] Moulton, F. R., 1912, p. 244.

[35] Becker, George F., 1910, p. 18.

[36] W. J. Gies.

salt in the ocean might afford a means of computing its age. Assuming a primitive fresh-water sea, Becker[37] in 1915 estimated the age of the ocean as between 50 and 70 million years, probably closer to the upper limit. The accumulation of sodium was probably more rapid in the early geologic periods than at the present time, because the greater part of the earth's surface was covered with the granitic and igneous rocks which have since been largely covered or replaced by sedimentary rocks, a diminution causing the sodium content from the earth to be constantly decreasing.[38] This is on the assumption that the primitive ocean had no continents in its basins and that the continental areas were not much greater than at the present time, namely, 20.6 per cent. to 25 per cent. of the surface of the globe.

AGE OF THE OCEAN CALCULATED FROM ITS SODIUM CONTENT[39]

1876.	T. Mellard Reade	
1899.	J. Joly	80– 90 million years.
1900.	J. Joly	90–100 million years.
1909.	Sollas	80–150 million years.
1910.	Becker	50– 70 million years.
1911.	F. W. Clarke and Becker	94,712,000 years.
1915.	Becker	60–100 million years.
1916.	Clarke	somewhat less than 100 million years.

From the mean of the foregoing computations it is inferred that the age of the ocean since the earth assumed its present form is somewhat less than 100 million years. The 63 million tons of sodium which the sea has received yearly by solution from the rocks has been continually uniting with its equivalent of chlorine to form the salt (NaCl) of the existing seas.[40] So with the entire present content of the sea, its sulphates as well as its chlorides of sodium and of magnesium, its potassium, its calcium as well as those rare chemical elements which occasionally enter into the life compounds, such as copper, fluorine, boron, barium—all these earth-derived elements were much rarer in the primordial seas than at the present time. Yet from the first the air in sea-water was much richer in oxygen than the atmosphere.[41] The primal sea was also devoid of those nitrogen compounds which are chiefly derived from the earth through the agency of the nitrifying bacteria. Those who hold to the hypothesis of the *marine origin* of protoplasm fail to account for the necessary proportion of nitrogenous matter there to begin with.

37 Becker, George F., 1910, pp. 16, 17.

38 Becker, George F., 1915, p. 201; 1910, p. 12.

39 After Becker, George F., 1910, pp. 3–5; and Clarke, F. W., 1916, pp. 150, 152.

40 Becker, George F., 1910, pp. 7, 8, 10, 12.

41 Pirsson, Louis V., and Schuchert, Charles, 1915, p. 84.

When we consider that these "chemical life elements," so essential to living matter, were for a great period of time either absent or present in a highly dilute condition in the ocean, it appears that we must abandon the ancient Greek conception of the origin of life in the sea, and again reach the conclusion that the lowliest organisms originated either in moist earths or in those terrestrial waters which contained nitrogen. Nitrates occasionally arise from the union of nitrogen and oxygen in electrical discharges during thunderstorms and were presumably thus produced before life began. Such nitrogen compounds, so essential for the development of protoplasm, may have been specially *concentrated* in *pools of water* to degrees particularly *favorable* for the *origin of protoplasm.*[42]

From terrestrial waters or soils life may have gradually extended into the sea. It appears, too, that every great subsequent higher life phase—the bacterial phase, the chlorophyllic algal phase, the protozoan phase—was also primarily of fresh-water and secondarily of marine habitat. It is probable that the succession of marine forms was itself determined to some extent by adaptation to the increasing concentration of saline constituents in sea-water. That the invasion of the sea upon the continental areas occurred at a very early period is demonstrated by the extreme richness and profusion of marine life at the base of the Cambrian.

As compared with primordial sea-water which was relatively fresh and free from salts and from nitrogen existing sea-water is an ideal chemical medium for life. As a proof of the special adaptability of existing sea-water to present biochemical conditions, a very interesting comparison is that between the chemical composition of the chief body fluid of the highest animals, namely, the blood serum, and the chemical composition of sea-water, as given by Henderson.[43]

Chemical Composition of Sea-water and of Blood Serum

"Life Elements"	In Sea-water	In Blood Serum
Sodium	30.59	39.0
Magnesium	3.79	0.4
Calcium	1.20	1.0
Potassium	1.11	2.7
Chlorine	55.27	45.0
SO_4	7.66	
CO_3	0.21	12.0
Bromine	0.19	
P_2O_5		0.4

That life originated in water (H_2O) there can be little doubt. The

42 Suggested by Professor W. J. Gies.

43 Henderson, Laurence J., 1908, II., p. 145.

fitness of water is maximal[44] both as a solvent in all the bodily fluids, and as a vehicle for most of the other chemical compounds. Further, since water itself is a solvent that fails to react with many substances (with nearly all biological substances) it serves also as a factor of biochemical stability. Water and the carbon dioxide of the atmosphere are the common source of every one of the complicated organic compounds and also the common end products of the materials yielding energy to the body. Proteins are made from supplies containing nitrogen material in addition.

In relation to Newton's law of action, reaction and interaction the most important property of water is its dielectric constant. Although itself only to a slight degree dissociated into ions it is the bearer of dissolved electrolytic substances and possesses a high power of electric conductivity, properties of great importance in the development of the electric energy of the molecules and atoms in ionization. Thus water is the very best medium of electric ionization in solution, and was probably essential to the mechanism of life from its very origin.[45]

Through all the electric changes of its contained solvents water itself remains very stable because the molecules of hydrogen and oxygen are not easily dissociated; their union in water contributes to the living organism a series of properties which are the prime conditions of all physiological and functional activity. The great surface tension of water as manifested in capillary action is of the highest importance to plant growth; it is also an important force acting within the formed colloids, the protoplasmic substance of life.

PRIMORDIAL ENVIRONMENT—THE ATMOSPHERE

It is significant that the simplest known living forms derive their "life elements" partly from the earth, partly from the water, and partly from the atmosphere. This was not improbably true also of the earliest living forms.

One of the mooted questions concerning the primordial atmosphere[46] is whether or no it contained free oxygen. The earliest forms of life were probably dependent on atmospheric oxygen, although certain existing bacterial organisms, known as "anærobic," are now capable of existing without it.

The primordial atmosphere was heavily charged with water vapor (H_2O) which has since been largely condensed by cooling. In the early period of the earth's history volcanoes[47] were also pouring into the atmosphere much greater amounts of carbon dioxide (CO_2) than at the

44 These notes upon water are chiefly from the very suggestive treatise "The Fitness of the Environment," by Henderson, Lawrence J., 1913.

45 Henderson, Lawrence J., 1913, p. 256.

46 Becker, George F., letter of October 15, 1915.

47 Henderson, Lawrence J., 1913, p. 134.

present time. At present the amount of carbon dioxide in the atmosphere averages about three parts in 10,000, but there is little doubt that the primordial atmosphere was richer in this compound which next to water and nitrogen is by far the most important both in the origin and in the development of living matter. The atmospheric carbon dioxide is at present continually being reduced by the absorption of carbon in living plants and the release of free oxygen; it is also washed out of the air by rains. On the other hand, the respiration of animals is continually returning it to the air. The large amount of aqueous vapor and of carbon dioxide in the primordial atmosphere served to form an atmospheric blanket which inhibited the radiation of solar heat from the earth's surface and also prevented excessive changes of temperature. Thus there was on the primal earth a greater regularity of the sun's heat supply, with more moisture, while the light supply from the sun was less intense and constant than at present. This is in general accord with the fact that the most primitive organisms surviving upon the earth to-day, the bacteria, are rather dependent upon heat than upon light for their energy. It is also possible that through the agency of thermal springs and the heat of volcanic regions primordial life forms may have derived their energy from the heat of the earth rather than from that of the sun.

The stable elements of the present atmosphere, for which alone estimates can be given, are essentially as follows:[48]

	By Weight	By Volume
Oxygen	23.024	20.941
Nitrogen	75.539	78.122
Argon	1.437	.937
	100.000	100.000

Since carbon is a less essential element[49] in the life-processes of the simplest bacteria, we can not agree with Henderson[50] that carbon dioxide was coordinate with water as a primary compound in the origin of life. It probably was subsequently utilized in the chlorophyllic stage of plant evolution.

Atmospheric carbon dioxide (CO_2) which averages about three parts in every 10,000, and water (H_2O) is always present in varying amounts; beside argon, the rare gases helium, xenon, neon, and krypton are present in traces. None of the rare gases which have been discovered in the atmosphere, such as helium, argon, xenon, neon, krypton, and niton—the latter a radium emanation—are at present known to have any relation to the life processes. Carbon dioxide exists in the atmos-

[48] Clarke, F. W., letter of March 7, 1916.

[49] Jordan, Edwin O., 1908, p. 66.

[50] Henderson, Lawrence J., 1913, pp. 138, 139.

phere as an inexhaustible reservoir of carbon, only slightly depleted by the drafts made upon it by the action of chlorophyllic plants or by its solution in the waters of the continents and oceans. Soluble in water and thus equally mobile, of high absorption coefficient, and of universal occurrence, it constituted a reservoir of potential energy for the development of plants and animals. Carbon dioxide in water forms carbonic acid, one of the few instances of biological decomposition of water. This compound is so unstable that it has never been obtained. Carbon dioxide is now produced not only within the atmosphere but also by the action of certain anærobic bacteria and molds without the presence of free oxygen, as, for example, through the catalytic action of zymase, the enzyme of yeast, which is soluble in water. Loeb[51] dwells upon the importance of the bicarbonates as regulators in the development of the marine organisms by keeping neutral the water and the solutions in which marine animals live. Similarly the life of fresh-water animals is also prolonged by the addition of bicarbonates.

Thus from the chlorophyllic stage onwards the compounds of carbon, hydrogen, and oxygen (C, H, O)[52] constitute a unique ensemble of fitness among all the possible chemical substances for the exchange of matter and energy both within the organism and between it and its environment. The "regulator" or "balancing" influence is exerted by the phosphates and upon the acidifying tendency of carbon dioxide. The carbon dioxide in respiration raises the hydrogen concentration of the blood. The phosphates restrain this tendency while the breathing apparatus, in response to stimulus from the respiratory center irritated by the hydrogen, throws out the excess of the latter.

51 Loeb, Jacques, 1906, pp. 96, 97.

52 Henderson, Lawrence J., 1913, pp. 71, 194, 195, 207, 231, 232.

(*To be continued*)